

# EVIDENCE OF SOLAR FLARE TRIGGERING DUE TO LOOP-LOOP INTERACTION CAUSED BY FOOTPOINT SHEAR-MOTION

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## ABSTRACT

We analyze multi-wavelength data of a M7.9/1N class solar flare which occurred on 27 April, 2006 from AR NOAA 10875. GOES soft X-ray images provide the most likely signature of two interacting loops and their reconnection, which triggers the solar flare. TRACE 195 Å images also reveal the loop-loop interaction and the formation of ‘X’ points with converging motion ( $\sim 30 \text{ km s}^{-1}$ ) at the reconnection site in-between this interacting loop system. This provides the evidence of progressive reconnection and flare maximization at the interaction site in the active region. The absence of type III radio burst during this time period indicates no opening of magnetic field lines during the flare energy release, which implies only the change of field lines connectivity/orientation during the loop-loop interaction and reconnection process. The Ondrejov dynamic radio spectrum shows an intense decimetric (DCIM) radio burst (2.5–4.5 GHz, duration  $\sim 3 \text{ min}$ ) during flare initiation, which reveals the signature of particle acceleration from the reconnection site during loop-loop interaction. The double peak structures at 4.9 and 8.8 GHz provide the most likely confirmatory signature of the loop-loop interaction at the flare site in the active region. RHESSI hard X-ray images also show the loop-top and footpoint sources of the corresponding two loop system and their coalescence during the flare maximum, which act like the current carrying flux-tubes with resultant opposite magnetic fields and the net force of attraction. We also suggest that the shear motion/rotation of the footpoint of the smaller loop, which is anchored in the opposite polarity spot, may be responsible for the flare energy buildup and then its release due to the loop-loop interaction.

*Subject headings:* Solar flare – coronal loops, magnetic field, magnetic reconnection,

particle acceleration

## 1. INTRODUCTION

Solar flare is a sudden explosion in the solar atmosphere during which the magnetic energy (stored in the twisted and sheared magnetic fields as well as in the current layers between interacting fields) is released in the form of kinetic energy of rapidly moving plasma, accelerated particles and thermal energy to heat-up the ambient plasma. This primary release of energy takes place in the corona and is accompanied by fast directed ejections (e.g., jets) of plasma, powerful flows of heat, and accelerated particles. They interact with the chromosphere and photosphere, and therefore, creating an extremely rich scenario of secondary physical processes observed as a solar flares.

It is generally believed and well supported by observations that magnetic reconnection is the key effect which plays the crucial role in annihilating the complex magnetic field structures and corresponding energy release. The solar flares are mainly distinguished in two categories, e.g., the confined and eruptive flares, which are usually triggered respectively in the closed and open morphology of overlying magnetic fields. The instabilities generated in the complex magnetic fields may be one of the most probable causes to drive/trigger the solar flares after the reconnection of unstable flux tubes with the neighbourhood field configuration. The emergence of unstable and helical twisted structures can trigger the flares followed by an eruption (Liu et al. 2008, 2007; and references cited there). However, the activation of twisted helical magnetic structures may also play a crucial role in the flare energy build-up and their initiation with failed eruption depending upon the surrounding magnetic field environment (Kumar et al. 2010, Srivastava et al. 2010 and references cited

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there).

Solar coronal loops may be considered as the current ( $\lesssim 10^{12}$  amp.) carrying conductors. Two current carrying conductors possess net attractive force if both have resultant currents in the same direction or resultant magnetic fields in the opposite direction depending upon their orientation with each other. Collisions between current carrying loops are considered as a cause of some solar flares (Sakai & de Jager 1996). Based on the loop orientations and size of the interaction region, the current carrying loop interactions are classified into three categories: (a) 1-D coalescence (I-type), (b) 2-D coalescence (Y-type), and (c) 3-D coalescence (X-type). The theoretical model of Gold & Hoyle (1960) firstly explains the flare triggering caused by interacting current carrying loops. However, it is not necessary that the field lines should be anti-parallel for the interaction of two current carrying conductors. There may be other mechanisms, e.g., footpoint shear motion and rotation, which can also destabilize the loop-system to trigger the flare and eruption. Stronger shear has more probability for the initiation of the solar flares and related eruptions (e.g., Tan et al. 2009 and references cited there). Yohkoh has also observed some of the flaring events which show three types of loop interaction (I, Y and X-type). In the above mentioned interactions, the 3-D X-type reconnection due to coalescence is the most realistic scenario in the active regions. The necessary condition for 3-D X-type interaction is that the length of the interaction region (L) should be comparable to the loop diameter (R) (Sakai & de Jager 1989).

Hanaoka (1996) has found evidence of the emergence of a small loop near one of the footpoints of a pre-existing large coronal loop using observations of various instruments including Yohkoh. The interaction of this loop with the larger loop causes flares, microflares and jets. Liu et al. (1998) have also observed the flare triggering by the I-type interaction of loop-systems. Falewicz & Rudawy (1999) have shown the flare energy release caused by two

successive X-type interaction of an expanding loop with two high-lying and nearly parallel loop-systems. Furthermore, Pohjolainen (2003) has also studied the series of flares from AR 8996 on 18-20 May, 2000 and provided the evidence of flare triggering due to loop-loop interaction with the observation of moving magnetic features around the sunspot region. Several authors have reported the loop-loop interaction as a cause of solar flares. However, further multiwavelength studies are needed to understand the flare triggering mechanism due to loop-loop interaction, and its responses in the various layers of the solar atmosphere. In spite of the loop-loop interaction, the flare triggering followed by solar eruptions (e.g., coronal mass ejection) can also be caused by the interaction of filaments system due to sunspot rotation (e.g., Kumar et al. 2010 and references cited there).

We know that the interacting current loops are not located in the vacuum or isolating medium, but they are lying in the highly-conducting plasma penetrated by frozen-in magnetic fields in the solar corona. From the beginning of the evolution of a current carrying loop-system, every change in the current carrying loop-system generates currents in the surrounding plasma and magnetic field. Therefore, we have to take into account an interaction not only between the loops but also with these new currents, in particular with screening current layers between the loops. Moreover, the frozen-in magnetic fields of an active region or an activity complex are typically strong in the corona and have their specific topology determined by the photospheric sources. Henoux & Somov (1987) were the first to show that these effects are essential and must be considered in terms of magnetic reconnection of field-aligned electric currents (see Section 2.4). On the other hand, if there were no current loops related with a twist of magnetic flux tubes at all, even in this case, three-dimensional reconnection between interacting magnetic fluxes gives such distribution of reconnected magnetic fluxes in the corona that two soft X-ray loops look like interacting with each other (Gorbachev & Somov 1989, 1990). That is the reason that the observations demonstrated such structures are usually considered as a direct evidence of the hypothesis

of two interacting currents.

In this paper, we present a multiwavelength study of M7.9/1N solar flare on 27 April, 2006 in AR NOAA 10875, which shows rare observational evidence of the coalescence and the interaction of two current carrying loops. We report a most likely multiwavelength signature of X-type interaction and coalescence instability in the active region which triggers the solar flare. In Section 2, we present multiwavelength observations of the event. We discuss our results and conclusions in the last section.

## 2. OBSERVATIONS AND DATA

The active region NOAA 10875 was located at S10 E20 on 27 April, 2006, showing  $\beta\gamma/\beta\gamma\delta$  magnetic configuration, and has produced M7.9/1N class solar flare. According to the GOES soft X-ray flux profile, the flare started at 15:45 UT, was at its maximum at 15:52 UT and ended at 15:58 UT. Figure 1 displays the flux profiles in the soft X-ray, soft X-ray derivative, hard X-ray and radio wavelengths. The flux derivative of soft X-ray matches well with the rise-up of hard X-ray flux profile. This implies that the accelerated electrons that produce the hard X-ray also heat the plasma that produces the soft X-ray, obeying the Neupert effect (Neupert 1968). More exactly, this means that the impulsive heating of the solar atmosphere by accelerated electrons can dominate its heating by thermal fluxes from the high-temperature source of flare energy (see Chapter 2 in Somov, 1992). So there is a causal connection between the thermal and nonthermal flare emissions. Further, the radio flux profile shows the sharp rise-up with double peak structure mostly in 4.9 and 8.8 GHz at 15:47 UT, which shows the gyrosynchrotron emission generated by the accelerated electrons at the reconnection (i.e. loop-interaction) site.

## 2.1. GOES SXI AND TRACE Observations

We have used GOES-SXI observations of the event (Hill et al. 2005; Pizzo et al. 2005). It is a broadband imager in the 6–60 Å bandpass that produces full-disk solar images with  $\sim 1$  minute cadence. The images consist of 512 pixel $\times$ 512 pixel with 5'' resolution. The FWHM of the telescope point-spread function is  $\sim 10''$ . A set of selectable thin-film entrance filters allows plasma temperature discrimination, i.e., open, three polyimide (thin, medium, and thick), and three beryllium (thin, medium, and thick). The open and polyimide filters are sensitive to the plasma below 2 MK. It is especially suitable for continuous tracking of coronal loops.

Figure 2 displays the selected images of GOES SXI before and during the flare activity. Two loop systems have been observed before the flare initiation. One lower loop system (indicated by red line) is underlying a higher loop-system (blue). Initially, brightening starts in the lower loop during flare initiation at 15:43 UT. This loop becomes more brighter as the flare progresses. The four footpoints of both the loop-systems become evident at 15:47 UT mainly due to the precipitation of the accelerated electrons from the interaction or reconnection site. The corresponding footpoints of both interacting loops are indicated by FP1 (L1) and FP2 (L1) for loop 1 and FP1 (L2) and FP2 (L2) for loop 2, respectively. As the plasma is heated-up due to the dissipation of kinetic energy of the accelerated electrons from the reconnection site, chromospheric evaporation takes place and it fills the interacting loop-system in the corona and these loops look like as if they are crossing to each other. Now the X-type configuration becomes evident at 15:49 UT. The flare maximum takes place at 15:52 UT. After the interaction between the loops, the orientation of the lower loop has changed into a more relaxed state. The SXI image taken during the decay phase of the flare (at 16:31 UT) evidently shows the orientation change of the lower loop-system.

In this Figure, the loop shown by red line is marked in the upper-left panel as rooted



somewhere close to  $X \approx -445''$ ,  $Y \approx -50''$ . However, in middle-left panel the left foot of this loop (marked by FP1(L1)) has co-ordinates at  $X \approx -440''$ ,  $Y \approx -70''$ . Therefore, the shift in the footpoint during the dynamical flare event is  $\Delta X = 5''$ ,  $\Delta Y = 20''$ . Presumably, this apparent displacement of the footpoint FP1(L1) may be due to the two reasons:

(a) A displacement directed out from the photospheric neutral line, therefore, it is related to the motion of the flare ribbons in the opposite directions. Such behavior is typical for the two-ribbon flares;

(b) A displacement directed parallel to the photospheric neutral line, which is related to the magnetic shear relaxation.

These two processes can jointly cause an increasing or decreasing distance between the footpoints. Investigations in the frame of a more detailed model should be done to interpret this feature. It is necessary to compare the kernel displacements observed during the flare with motions and evolution of magnetic fields in the photosphere before the flares (see Somov et al., 2002).

TRACE (Transition Region and Coronal Explorer) provides the opportunity to observe the Sun from chromosphere to corona (Handy et al. 1999). We have used TRACE 195 Å (Fe XII,  $T \sim 1.5$  MK) and 1600 Å ( $T \sim 4000$ -10000 K). The field of view for each image is  $1024 \times 1024$  with  $0.5''$  pixel $^{-1}$  resolution. The typical cadence for TRACE images is  $\sim 20$ -60 sec. Figure 3 displays the selected TRACE 195 Å images during the flare activity. TRACE data have been calibrated and analyzed using standard routines in the solarsoft library <sup>2</sup>. During the flare initiation, brightening was observed along both sides of the photospheric neutral line. Two bright sheared structures are observed at 15:46 UT. The image at 15:48 UT shows the loop-loop interaction and formation of an ‘X’ point in between the

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<sup>2</sup><http://hesperia.gsfc.nasa.gov/ssw/trace/>

interacting loop-system. Many interacting small flux threads/tubes may be seen in this image. After the X-type interaction during the impulsive phase of the flare, it seems that the loop threads are changing their footpoint connectivities. This is the signature of an ongoing reconnection process in the same global configuration of the active region. During 15:42–15:46 UT, the two interacting loops are visible in the soft X-ray GOES/SXI images, however, they are not visible in the TRACE images of the same duration. The GOES/SXI images represent the high temperature and high coronal part of the loop systems, while the TRACE images show the lower part of the loop systems joining the two brightened ribbons. In the pre-flare state, the GOES/SXI images show the loop segments visible due to the emission of the soft X-ray during loop-loop interaction, while at the same time the plasma at EUV temperature band is not uploaded in the lower segments of the two loops to brought them as visible as GOES/SXI images. However, near the flare maximum and even after the flare, the interacting loop systems are clearly evident in both X-ray as well as in EUV, and imply the presence of plasma at various temperatures. Since, we see the different segments of the interacting loop-systems in GOES/SXI and TRACE images. Therefore, they look like with a different orientations as the apex part may be more tilted compared to the lower segments. We can identify the four footpoints of the associated interacting two loop-systems. During the interaction time, the thickness of the interaction region (indicated by arrows) reduces during the impulsive phase of the flare and it seems that the orientation of the loops is changed during the flare maximum (refer to image at 15:50 UT and onwards images). During the sharp impulsive phase, the footpoints of the loop systems do not show significant changes (see TRACE movie). It means that the reconnection point is mostly fixed, i.e., the loops interaction site. The loop-system morphology becomes simple and relaxed during the decay phase of the flare as observed in SXI images (see SXI image at 16:31:01 UT). The thickness of the interaction region is plotted against the GOES soft X-ray flux profile (refer to Figure 4). This plot reveals that the X-ray flux rises up as

the thickness of the interaction region decreases. This may be the most likely signature of ongoing reconnection at the loops interaction site. From the linear fit, the typical converging speed is estimated as  $\sim 30 \text{ km s}^{-1}$ . This speed may be related with the typical inflow speed as observed in other flares (Tsuneta et al. 1997; Yokoyama et al. 2001).

We have overplotted MDI contours over TRACE 195 Å image and vice versa (refer to Figure 5). Left footpoints [FP1(L1) and FP2(L2)] of the associated loop-systems are anchored in positive polarity field regions whereas the right footpoints [FP1(L2) and FP2(L1)] are anchored in the negative polarity regions.

For investigating the overlying magnetic field environment of this active region, we have used the potential field source surface (PFSS) extrapolation (Altschuler & Newkirk 1969; Schatten et al. 1969) before the flare event at 00:05 UT (see left panel of Figure 6). The right panel of Figure 6 displays  $H\alpha$  image observed at Meudon, which shows flare ribbons during the decay phase (at 16:16 UT) of the flare. It shows mainly four bright kernels, which are the regions where most of the energy flux is concentrated i.e. the sites of particle precipitation. These are the footpoints of the corresponding reconnecting loop-system. These observations are in favour of loop-loop interaction mechanism. For comparison, the location of the flare ribbons polarities is denoted by corresponding ‘+’ (red) and ‘-’ (blue) signs in SOHO/MDI image of the active region (AR10875) with its coronal field extrapolation. The coronal magnetic field topology is on average also in agreement with TRACE and SXI observations. Figure 7 displays the TRACE 1600 Å images during the flare event. Two ribbons, located on the both side of neutral line are observed at 15:44 UT. Left side ribbon shows the sheared ‘S’ shaped structure, whereas the ribbon at the right side shows simple structure.

## 2.2. Radio and RHESSI Observations

We have used Ondrejov dynamic radio spectrum data (2–4.5 GHz) during the flare (Jiricka et al. 1993; Jiřicka & Karlický 2008). This radiospectrograph uses a 3-m dish and wide band horn antenna as primary feed. The time resolution is 10 ms and the frequency band is divided into 256 channels, which mean the frequency resolution is of about 10 MHz. Figure 8 (upper panel) displays the Ondrejov dynamic radio spectrum on 27 April, 2006 showing the intense DCIM radio burst during flare initiation. Moreover, there was no Type III burst during this time period (checked with Wind/WAVES spectrum). That means the opening of field lines did not take place during the flare energy release (i.e. during reconnection). The DCIM burst starts in  $\sim 2.5$ –3 GHz frequency and continues upto 4.5 GHz. This frequency range covers the typical range of heights corresponding to reconnection site. The burst starts at 15:46 UT and continues upto 15:49 UT for the duration of  $\sim 3$  minutes. The observed DCIM bursts reveal the signature of particle acceleration from the reconnection site during loop-loop interaction/coalescence.

The US Air Force operates four solar radio observatories at various locations around the world. These are collectively known as the Radio Solar Telescope Network or RSTN. Each observatory monitors solar radio emissions on 8 discrete fixed frequencies (245, 410, 610, 1415, 2695, 4995, 8800 and 15400 MHz) as well as low frequency spectral emissions in the VHF band. We have used the radio flux data (1 sec cadence) from Sagamore Hill. We have selected four radio frequency bands of 2695, 4995, 8800 and 15000 MHz, which show significant variations in the flux profiles. The radio burst is observed during  $\sim 15:46$ – $15:49$  UT (Figure 8, lower panels). The radio flux profiles in 4900 and 8800 MHz show double peak structures associated with the coalescence of the loop-systems. It may be noted that second double peak structure is stronger in comparison to the first one, which shows that the superthermal electrons accelerated from a higher amount of pre-accelerated electrons

generated the last double peak (Karlický & Jiříčka 2003). After this burst, we observe the quasi-periodic oscillations specially in 4995, 8800 and 15400 MHz frequencies during  $\sim 15:48$ – $15:51$  UT for the duration of  $\sim 3$  minutes, which may be attributed to modulations by MHD oscillations or nonlinear relaxational oscillations of wave particle interactions. Therefore, MHD waves can modulate the emissions from the trapped electrons (Aschwanden 2004).

The absence of Type III radio burst suggests the absence of opening of field lines during the reconnection process. Further, we do not see plasmoid ejection in soft X-ray images from the reconnection site. Therefore, the DCIM radio burst can not be interpreted as ejected plasmoid from the reconnection site. It should be noted that the burst starting frequency is  $\sim 2.5$ – $3$  GHz, which corresponds to the typical height of post flare loops and originates in magnetic reconnection regions (i.e. plasma density of  $\sim 10^{10}$ – $10^{11}$  cm $^{-3}$ ) (Aschwanden 2004). As this burst continuation can be seen upto 4.5 GHz in the radio spectrum and further in single frequencies radio flux profiles ( i.e. in 2.6, 4.9, 8.8 and 15 GHz). Therefore, we interpret these emissions due to nonthermal electrons accelerated from the reconnection site along the soft X-ray loop systems. This may be confirmed by the soft X-ray image at 15:47:02 UT, which shows the four footpoints due to precipitated electrons during the time of radio burst.

The evolution of hard X-ray sources in two selected energy bands (12–25 and 25–50 keV) of RHESSI instrument is shown in Figure 9 and 10. These images have been reconstructed using PIXON method. In both the energy bands, the two separated loop-top sources are visible at 15:49 and 15:50 UT and then their coalescence resulting into a single source (at 15:54 and 15:56 UT). These images also provide the evidence of two loops coalescence.

### 2.3. Evolution of Active Region

Figure 11 displays the selected images of TRACE white-light of active region on 27 April, 2006. FP1 (red) and FP2 (blue) in the top first image show the ‘+ve’ and ‘-ve’ footpoints (indicated by arrows) of the lower loop system respectively. The careful investigation of the TRACE movie reveals the linear/shear motion of small sunspot of negative polarity (indicated by blue contours) across the neutral line. We have made the time-distance plot to quantify the linear translational motion of the sunspot. From the linear fit to the data points, the speed of this motion is estimated as  $\sim 0.2 \text{ km s}^{-1}$  ( $662 \text{ km h}^{-1}$ ) (see Figure 13). To identify the footpoint of the related loop-system anchored in this spot, we overlaid MDI and TRACE 195 Å contours over the white-light image (refer to Figure 12, left). This image reveals that one footpoint of the loop-system is anchored in this spot. In order to view the photospheric horizontal flow pattern in and around the active region, we use the Fourier Local Correlation Tracking Technique (FLCT) on SOHO/MDI images. The FLCT method is described by Fisher & Welsch (2008). The main input parameters for this technique are, two images f1 and f2, the pixel separation scale ( $\Delta s$ ) and time separation ( $\Delta t$ ), and a Gaussian window size scale ( $\sigma$ ). This routine calculates the velocity (2D) by maximizing the cross-correlation of each image when weighted by the Gaussian window centered on each pixel location. In our study, we use the two SOHO/MDI frames at different times before the flare. After a careful investigation, a Gaussian window with a standard deviation of  $15''$  was chosen. The right panel of Figure 12 displays the photospheric velocity map obtained from FLCT technique using SOHO/MDI magnetograms. The longest arrow corresponds to velocity of  $0.291 \text{ km s}^{-1}$ . It may be noted from the flow map that the small, negative polarity spot shows the clockwise shear flow motion whereas the positive polarity region (in which another footpoint was anchored of the lower loop-system) shows counter-clockwise flow motion. This linear translational motion as evident in TRACE white light images as well as velocity shear flows as evident

in FLCT images near the spots most likely indicate the triggering of the shear in their locations. This physical mechanism most likely plays a role in the energy build-up for flare and generates the coalescence instability in the lower loop-system.

## 2.4. Magnetic Topology of the Interacting Loop-Systems

In this Section, we discuss the large-scale structure of a magnetic field responsible for the solar flare. The soft X-ray image of the flare clearly reveals the two large solar loops (L1 and L2) crossing to each other and exhibit the X-type interaction. The chromospheric images ( $H\alpha$  and TRACE 1600 Å) show the two ribbon morphology with the four kernels, i.e. four footpoints of the reconnected loops. We illustrate these features of the interacting loop-systems in terms of the *topological* models (see ch. 3 in Somov (2007)). Figure 14 displays the field lines that connect the  $H\alpha$  kernels: FP1 (L1) with FP2 (L1), and FP1 (L2) with FP2 (L2). The shadowed regions FR1 and FR2 indicate the flare ribbons. They are located on both sides of the photospheric neutral line NL. Chromospheric evaporation along the reconnected field lines creates the SXR loops that look like they are crossing or touching each other somewhere near the top of a magnetic-field separator X. The loops and ribbon morphology shown in the observations qualitatively matches with this cartoon.

It is very likely that, in addition to what is shown in Figure 14, the electric currents and twisted magnetic fields can be created inside the interacting loops by some under-photospheric or photospheric mechanism observed in the photosphere as shear motions or rotations. Such currents certainly must exist in complex active regions with sunspot rotation and large-scale photospheric shear flows. If the currents are mostly parallel, they attract each other and can give energy to a flare (Gold & Hoyle 1960). On the other hand, according to the simplified topological model presented in Figure 14, the flare energy comes from an interaction of magnetic fluxes that can be mostly potential. If this would

be the case, the flare energy should be stored before a flare mainly in slowly-reconnecting current layer at the separator of coronal magnetic field. This possibility seems to be in agreement with the quadrupole reconnection model of the solar flares. The morphology of the loops is also in agreement with the PFSS extrapolation of photospheric magnetic fields into the corona. Therefore, we consider both the models firstly from the view-point of global magnetic configuration of a quadrupole-type active region taking into account the interacting electric currents.

Figure 15 illustrates the possible configuration of two large scale coronal currents  $J_1$  and  $J_2$  distributed inside two different magnetic cells, i.e. the two magnetic fluxes of different linkage that interact and reconnect at the separator  $X$ . The two field lines  $B_1$  and  $B_2$  belong to the magnetic cells that connect the kernel FP2 (L2) with FP1 (L2) and the kernel FP2 (L1) with FP1 (L1) respectively. The coronal currents are distributed somehow inside the two different magnetic cells and shown schematically the total currents  $J_1$  and  $J_2$  along the field lines  $B_1$  and  $B_2$ .

If the field lines  $B_1$  and  $B_2$  near the current layer along the separator have an opposite direction component, then they can be reconnected. If the two current systems  $J_1$  and  $J_2$  flow more or less in the same direction, then they also attract each other according to Gold & Hoyle (1960). The components of the magnetic field transversal to the separator reconnect together with electric currents flowing along them (Henoux & Somov 1987; Somov 1992). In this way, with a perpendicular magnetic field inside the place of interruption, magnetic reconnection can create local interruptions of the electric currents in the solar atmosphere. If these currents are highly concentrated, their interruption can give rise to strong electric fields that accelerate the energetic particles and can contribute significantly to the flare energetics.

What factors do determine the rate of magnetic reconnection in the current layer at



the separator? – Let us consider the magnetic fields created by the currents  $J_1$  and  $J_2$ . These additional or secondary fields play the role of the longitudinal magnetic field near the reconnecting current layer. Being superimposed on the large-scale potential field, they create the two types of field line spirals, i.e., left-handed and right-handed. When looking along the positive direction of the field lines  $B_1$  and  $B_2$ , we see the two opposite orientations for the spirals namely to the right for the *dextral* structure and to the left for the *sinistral* one. Depending on this handedness property known as a *chirality* also that depends on the angle between the currents  $J_1$  and  $J_2$ , magnetic reconnection of electric currents will proceed faster or slower (Henoux & Somov 1987).

As evident in the observations as well as in the theoretical baseline, the X-type reconnection may produce the plasma jets. However, we have no observational signature of such jets in our observations. In the flare under consideration, the reconnected fast outflows from a current layer relax quickly because they interact with (i) closed field lines of a quadrupole-type of the active region (recall that there was no type III radioburst, thus the opening of field lines did not take place during the flare energy release, i.e. reconnection); (ii) chromospheric evaporation upflows (the energy released in closed magnetic configuration goes into impulsive heating of the upper chromosphere to high temperatures that is why the soft X-ray images become so bright quickly).

### 3. SOME THEORETICAL ESTIMATIONS

The RHESSI temporal images (12-25 and 25-50 keV) reveal the coalescence of the loop-top sources of the interacting loop system. The two loop-top sources merge approximately vertical in the RHESSI field of view. Therefore, the lower bound change of the distance of the two approaching loops is

$$\Delta l_{coal} \approx 22000 \text{ km} \tag{1}$$

and the elapses time is

$$\Delta\tau_{coal} \approx 420 \text{ s} \quad (2)$$

The coalescence instability may activate in the observed interacting loops system, which is the effect that merges the two isolated magnetic islands into a single one (Haruki & Sakai 2001a,b; Aschwanden 2004). This type of instability evolves in two phases, i.e. First phase in pairing of the current filament/loops as in ideal MHD process, while the second as the resistive phase of pairwise reconnection between the approaching current carrying flux tubes. The numerical MHD simulations reveal the different phases of coalescence instability in ideal/resistive solar plasma (Schumacher & Kliem 1997).

The characteristic time scale of the ideal phase of coalescence instability is the multiple of Alfvénic transit time (Aschwanden 2004):

$$\tau_{coal} = \frac{1}{q_{coal}} \cdot \frac{l_{coal}}{v_A}, \quad (3)$$

where

$$q_{coal} = \frac{u_{coal}}{v_A}, \quad (4)$$

The  $l_{coal}$ ,  $u_{coal}$  and  $v_A$  are respectively the distance between approaching loops, approaching velocity and local Alfvénic speed. Using equation (3) and (4), the differential coalescence speed

$$\Delta u_{coal} = \frac{\Delta l_{coal}}{\Delta \tau_{coal}}, \quad (5)$$

Therefore, using the observationally estimated values as mentioned in equation (1) and (2), we get the average coalescence speed as  $\sim 52 \text{ km s}^{-1}$ . TRACE 195 Å images also show the interacting and paired loops. Using these images, the projected distance-time profile of the interaction region (i.e. converging motion at the interaction site) has been presented in Figure 4. The average converging speed of the interaction region is estimated as  $\sim 30 \text{ km}$

$\text{s}^{-1}$ . The approximate approaching velocity of one magnetic island of a loop is evident as  $\sim 26 \text{ km s}^{-1}$ . The resemblance in these two speeds is in agreement with loop coalescence.

By assuming the typical Alfvénic speed at the interaction region as  $\sim 1000 \text{ km s}^{-1}$  and the projected distance between the approaching loops ( $\Delta l_{\text{coal}} \approx 22000 \text{ km}$ ), the estimated Alfvénic transit time of the region will be  $\sim 22 \text{ s}$ . Therefore the coalescence will occur  $\sim 20 \tau_A$  for our observation, which is rather longer as predicted in various simulation results explained by Sakai & de Jager (1996) as well as Tajima et al. (1982) under various assumptions of the model atmosphere. However, for  $L \sim 62800 \text{ km}$ ,  $\tau_A = 16 \text{ s}$ , the Reynolds number ( $S=R$ ) = 500,  $n_e = 10^{10} \text{ cm}^{-3}$  and  $B_Z = 90 \text{ G}$ , Milano et al. (1999) have found that two loops coalesce at  $t = 11\tau_A$  and the magnetic energy and even its dissipation enhanced. The loop coalescences time depends upon various atmospheric parameters, and therefore further simulations will be interesting to study the dynamics and energetics of our observed coalesced loops.

We can estimate the amount of energy ( $\mathcal{E}_c$ ) available due to coalescence instability (Tajima et al. 1982; Smartt et al. 1993) by:

$$\mathcal{E}_c \approx \frac{LB^2a^2}{2} \ln \frac{L}{a} \quad (6)$$

where  $L$ ,  $B$  and  $a$  are length of the reconnecting region, loop magnetic field and radius of current loop respectively. We take  $B \approx 100 \text{ G}$ ,  $L \approx 22000 \text{ km}$  and  $a \approx 11000 \text{ km}$ , which gives

$$\mathcal{E}_c \approx 1.0 \times 10^{31} \text{ ergs}. \quad (7)$$

Therefore, this value is comparable with the energy released during M-class flare.

In general, the total magnetic field energy of the currents generated by photospheric vortex flows, sunspot rotation or shear flows in the photosphere can exceed the energy of even the largest flares. However, in contrast to thin current layer at the separator, these

currents are typically dispersed over a large volume of magnetic flux tubes in the corona. The dissipation rate of the currents so distributed in the coronal plasma of very high conductivity is vanishingly small. However, their interaction with each other and with the current layers at the separator is not small and must be treated within the framework of the global electrodynamical coupling of a flare active region or complex.

As we saw in Section 2.4, a distinctive feature of this interaction is that the separator is orthogonal (in the sense of the magnetic field topology) to both systems of electric currents  $J_1$  and  $J_2$ . For this reason, not only the magnetic field components associated with the current layer, but also the longitudinal (guiding) components with respect to the separator are reconnected. Therefore, not only the energy associated with the current layer at the separator, but also a part of the energy of the currents generated by the photospheric vortex flows, sunspot rotation and shear flows is released in the flares (Henoux & Somov 1987), see also Somov et al. (2002).

All the above have been concerned with the large-scale structure of magnetic fields and electric currents in large solar flares that can be qualitatively described in the main features by the simplified topological models. However, in actual flares there are many different structures of different scales including the smallest ones. In the flare under consideration, we see many interacting small flux threads/tubes (e.g., Figure 3). Moreover, the image at 15:48 UT in this figure shows the loop-loop interaction and formation of 'X' point in between the interacting loop-system. So, it is likely that the observed flare was caused by interactions of not two but the multitude of the loops, forming more-or-less parallel systems and visible in low-resolution images as single wide loops. From theoretical point of view, this presumably means that the distributed currents  $J_1$  and  $J_2$  are deeply pinched in many thin current filaments. Therefore, we observe some average picture of reconnection with some average reconnection rate.

#### 4. DISCUSSION AND CONCLUSIONS

We present the rare observational evidence of X-type loop-loop interaction associated with M7.9/1N flare. The coronal images observed by GOES SXI and TRACE 195 Å evidently show the interacting loop-system. TRACE white-light images reveal the sunspots shear motion (negative polarity) across the neutral line. This shear motion probably might have produce the destabilization in the associated loop-system and cause the loop-interaction followed by the flare. On the basis of multiwavelength observations, we draw a schematic cartoon to explain the whole event scenario (see Figure 16). Before the flare there was two loop systems visible in SXI images. One higher loop in N-S direction and another smaller loop system in E-W direction lying below this higher loop system. Due to the shear motion of the right footpoint (anchored in negative polarity) of smaller loop system, the loop becomes unstable and rises up due to instability and reconnects with the overlying higher loop system resulting X-type interaction in association with flare event. After the flare event, the connectivity of the smaller loop system changed into the relaxed state.

The regular variation of 4.9 and 8.8 GHz radio flux and accompanying flare effect observed during 27 April, 2006 are interpreted using X-type loop interaction model. We found the oscillatory behavior with double peak structure. Double peak in the radio flux gives the support for loop-interaction model (Sakai et al. 1986). According to the theoretical model, the double peak structure is more pronounced, when the currents in the two loops are sufficient for the explosive coalescence. Individual peak belongs to the electric field variation at the reconnection site. This electric field accelerates the electrons which generate the radio emission. The cause of quasiperiodic oscillation is as follows: after explosive reconnection of poloidal magnetic fields taking place at the ‘X’ point between approaching current loop and two plasma blobs pass through each other and overshoot

(an approach that fails and gives way to another attempt), resulting the repetition of the process. Kliem et al. (2000) also proposed a model in which the pulsations of the radio flux are caused by quasi-periodic particle acceleration episodes that result from a dynamic phase of magnetic reconnection in a large-scale current sheet. The reconnection is dominated by repeated formation and sub-sequent coalescence of magnetic islands, while a continuously growing plasmoid is fed by newly coalescing islands. In our case, the coalescence speed of  $52 \text{ km s}^{-1}$  is much smaller than the Alfvén velocity of  $\sim 1000 \text{ km s}^{-1}$ . The preflare stage in which multiple current filament structure might be generated due to the photospheric shear motion across the neutral line. The photospheric shear motion can give rise to plasma currents along the potential magnetic field produced by the sunspots nearby the active region. As the shear motion proceed, the current density may increase and current loop might move up, associated with relaxation of magnetic tension (Sakai et al. 1986). The absence of type III burst during flare energy release confirms the connectivity change and no opening of field lines. In addition, coalescence of hard X-ray sources also confirm the loop-loop interaction.

Sakai et al. (1986) presented the physical characteristics of the explosive coalescence of current loops through computer simulation and theory and mentioned canonical characteristics of the explosive coalescence as (i) impulsive increase of kinetic energy of electrons and ions (ii) simultaneous heating and acceleration of particles in high and low energy spectra (i.e. Neupert effect) (iii) quasi-periodic amplitude oscillations in field and particle quantities (iv) a double peak (or triple peak) structure in these profiles. Our observations clearly matches with all the above mentioned characteristics of the explosive coalescence and provide a unique evidence of X-type loop-loop interaction satisfying theories and simulations.

The interaction of large-scale current-carrying loops should be considered as a part of

the global electrodynamic coupling in flare-productive active regions and active complexes as discussed in Section 2.4. On the one hand, the potential magnetic field in the corona determines a large-scale structure of active regions while the reconnecting current layers at separators in the corona together with other non-potential components (see Section 14.5 in Somov, 2007) of magnetic field determine energetic and dynamics of large flares. On the other hand, two large-scale current-carrying loops emerging from under the photosphere have the sufficient energy to provide a large flare too by their interaction and coalescent instability as considered in this paper. Moreover, these two currents could be incorporated in the large-scale structure with reconnecting current layer.

The principal question is in the relative role of two distinct sources of free magnetic energy: the interaction of magnetic fluxes, and the interaction of electric currents as demonstrated in this paper. Clearly the answer depends on the relation between: (a) the photospheric flows which create the preflare current layers at the separators, (b) the photospheric shear flows which induce the current layers extending along the separatrices (Somov et al. 2002), and (c) the other photospheric flows like sunspot rotations which twist the magnetic flux tubes. In any case, the separator is a special place where a fast conversion of free magnetic energy into bulk plasma motions, heat flows and energy of accelerated particles can take place.

In conclusions, we find the rare multiwavelength observational signature of the loop-loop interaction and triggering of the M-class flare, which is consistent with the earlier developed theories and simulations. However, further detailed multiwavelength studies should be carried out statistically by analyzing such events to shed more lights on the dynamics and energetics related to the flare and eruptive phenomena related to loop-loop interactions.

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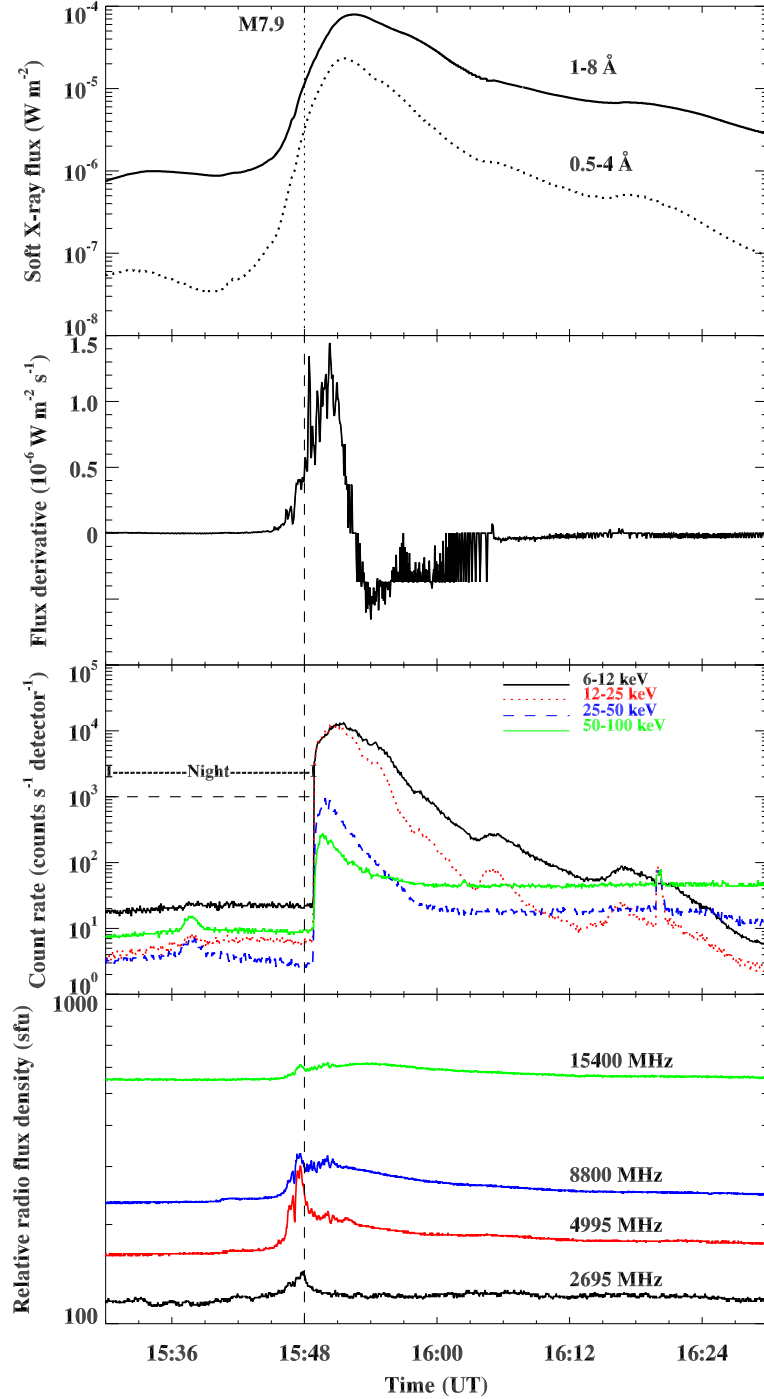


Fig. 1.— Soft X-ray flux, flux derivative, RHESSI and radio flux profiles for the M7.9 flare event on 27 April, 2006. The soft X-ray flux derivative matches well with the hard X-ray flux profile. This implies that the accelerated electrons that produce the hard-X-ray also heat the plasma that produces the soft X-ray (Neupert effect). The dotted line in the third panel indicates the RHESSI night time.

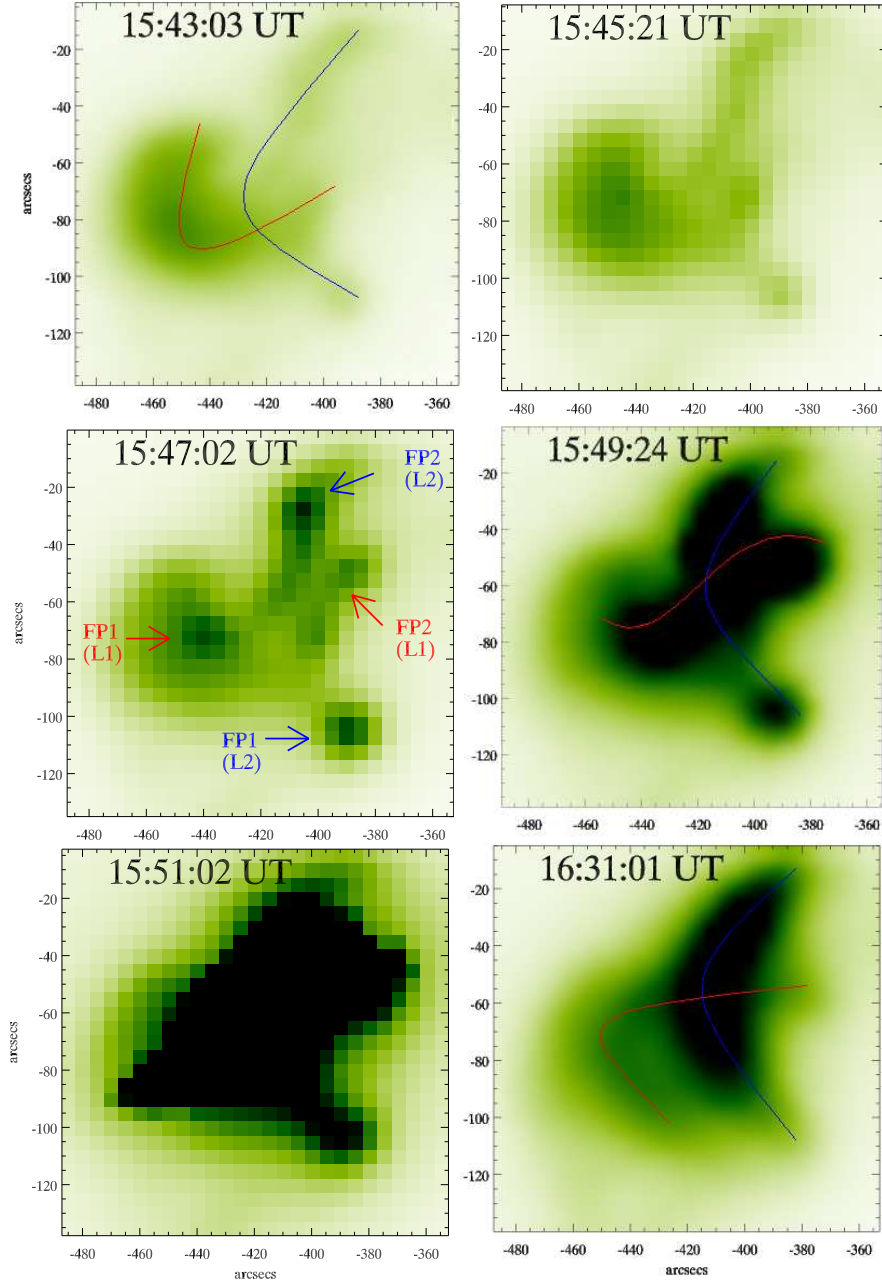


Fig. 2.— GOES Soft X-ray coronal negative images (6–60 Å) showing the flare evolution with the interaction of two coronal loops on 27 April, 2006. The upper left panel shows a lower loop system (blue) underlying a higher loop system (red). The lower loop first looks brighter during flare initiation. The middle left panel shows the corresponding footpoints of both interacting loops indicated by FP1 (L1) and FP2 (L1) for loop 1 and FP1 (L2) and FP2 (L2) for loop 2, respectively. The bottom left panels shows the flare maximum due to loop-loop interaction and the bottom right panel indicates the simplified 2 loops after the flare energy release.

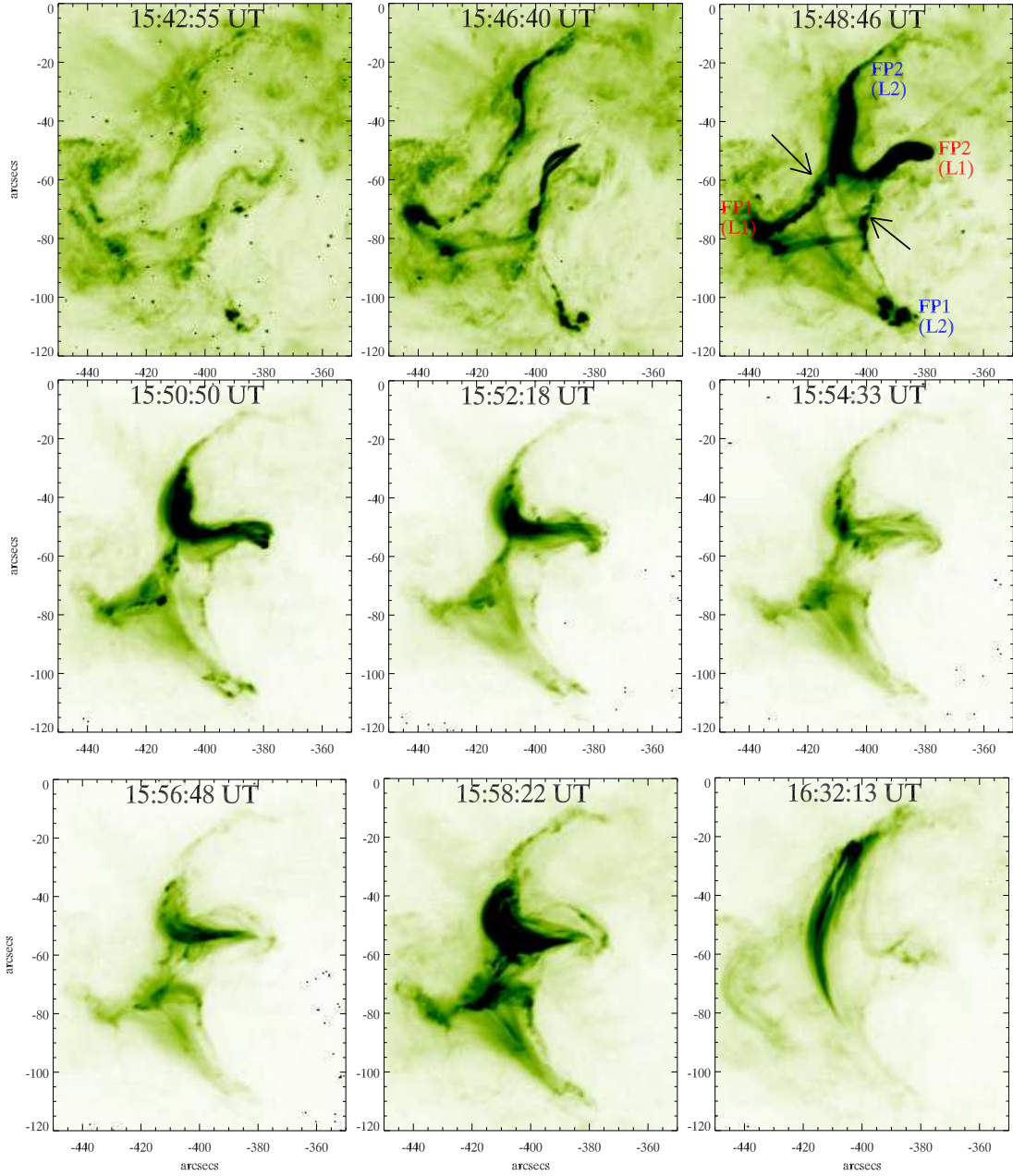


Fig. 3.— TRACE 195 Å negative images showing the flare evolution with the interaction of two coronal loops on 27 April, 2006. The upper and middle panels show approaching and interacting loops. The flare initiation takes place as the loops approach and maximizes at the time of interaction. The corresponding footpoints of the interacting loops are indicated by FP1 (L1) and FP2 (L1) for loop 1 and FP1 (L2) and FP2 (L2) for loop 2 respectively. The arrows indicate the interaction region/reconnection site. The bottom right panel shows the relaxation and orientation changes of the loops after interaction.

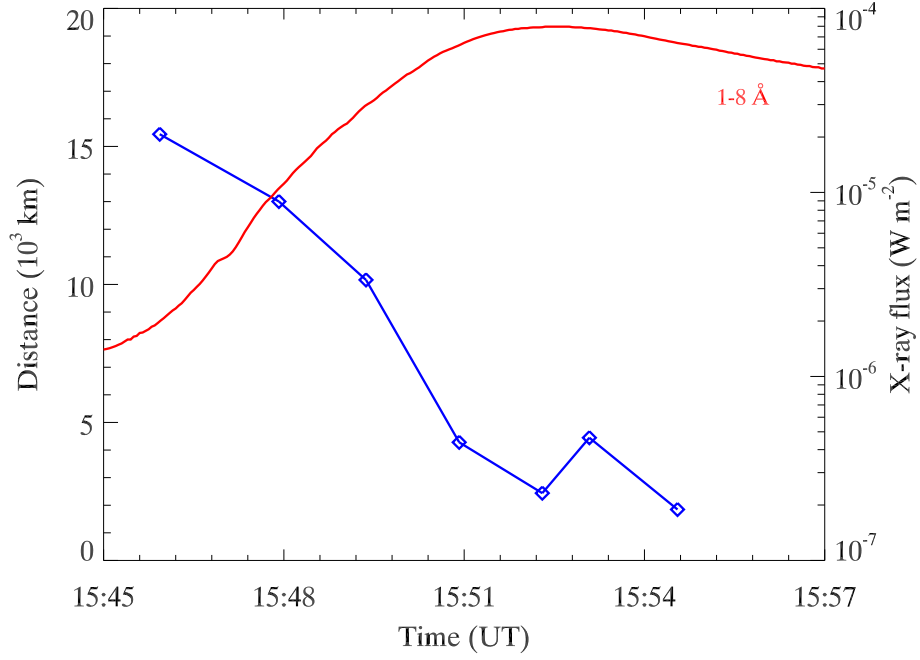


Fig. 4.— The thickness of interaction region shown by blue curve (estimated from TRACE 195 Å images) plotted against GOES soft X-ray flux profile (red curve). This plot reveals that as the thickness of interaction region decreases, the soft X-ray flux increases. This may be the most likely signature of ongoing reconnection at the site of loops-interaction. The typical converging speed of interacting region is  $\sim 30 \text{ km s}^{-1}$ .

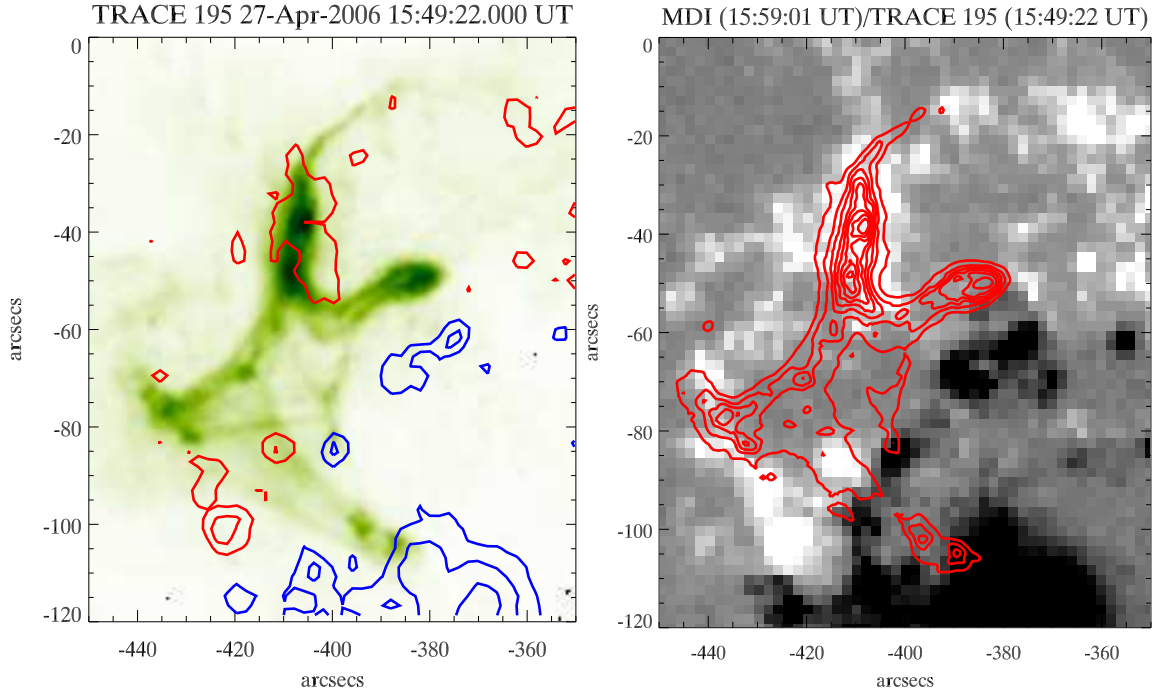


Fig. 5.— Left: MDI contours overlaid on TRACE 195 Å images during flare maximum (Blue contours indicate the negative whereas red contours show the positive polarity sunspots). The contour levels are  $\pm 500, \pm 1000, \pm 2000, \pm 3000$  G. Right: TRACE 195 Å contours overlaid on MDI magnetogram (Black=negative, White=positive).



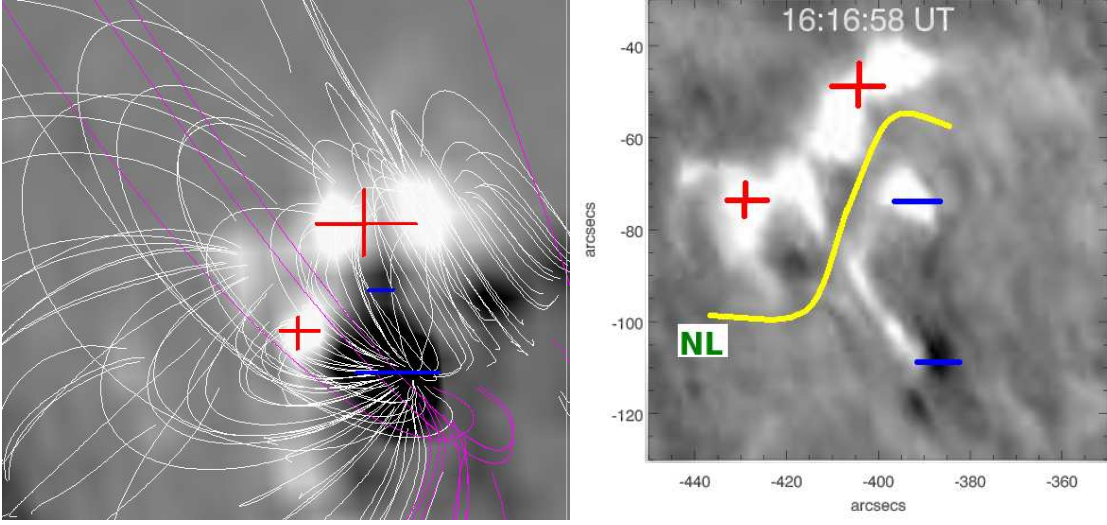


Fig. 6.— Left: PFSS (Potential Field Source Surface) extrapolations using SOHO/MDI magnetogram at 00:05:00 UT on 27 April, 2006. Right: H $\alpha$  image during the decay phase of the flare showing flare ribbons on the both side of neutral line (NL), indicated by yellow line. The polarity at the location of flare ribbons is indicated by ‘+’ and ‘-’ symbols. For comparison, the locations of the flare ribbon polarities are denoted by ‘+’ (red) and ‘-’ (blue) signs in the left panel.

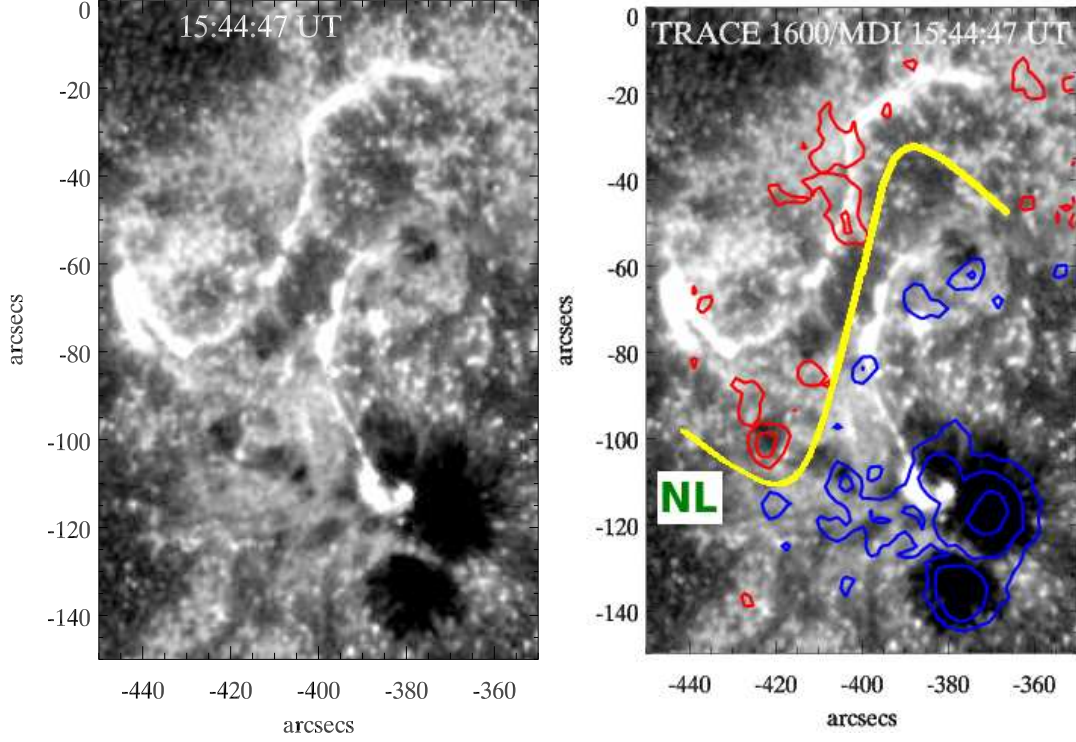


Fig. 7.— Left: TRACE 1600 Å images showing the the morphology of flare ribbons during the flare. Right: SOHO/MDI magnetic field contours overlaid on TRACE 1600 Å image. Red one indicate the positive polarity whereas blue one show the negative polarity fields. The contour levels are  $\pm 500, \pm 1000, \pm 2000, \pm 3000$  G. Ribbons are formed on the both sides of neutral line (NL), drawn by yellow color.

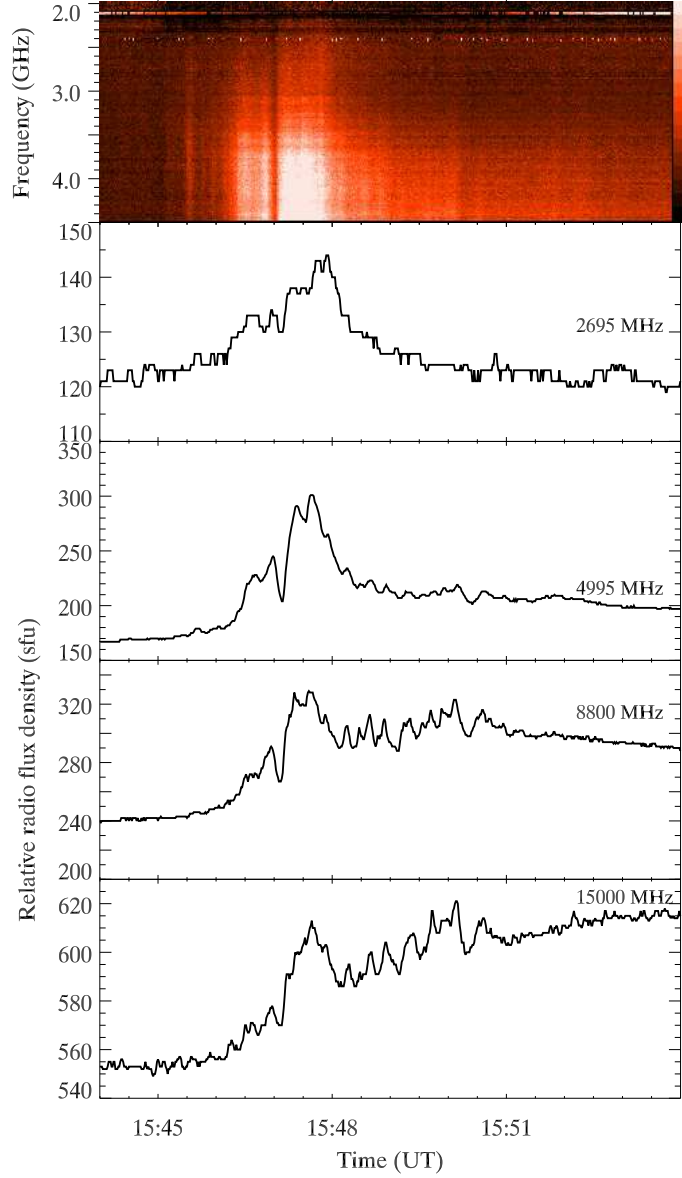


Fig. 8.— Top panel: Ondrejov dynamic radio spectrum on 27 April, 2006 showing the intense DCIM radio burst during flare initiation. Additionally, there was no Type III burst during this time period (checked with Wind/WAVES spectrum). That means the opening of field lines did not take place during the flare energy release (i.e. during reconnection). The observed DCIM burst is the signature of particle acceleration from the reconnection site during loop-loop interaction/coalescence. Bottom panel: RSTN 1 sec cadence radio flux profiles in 2.6, 4.9, 8.8 and 15 GHz frequencies observed at Sagamore-Hill station.

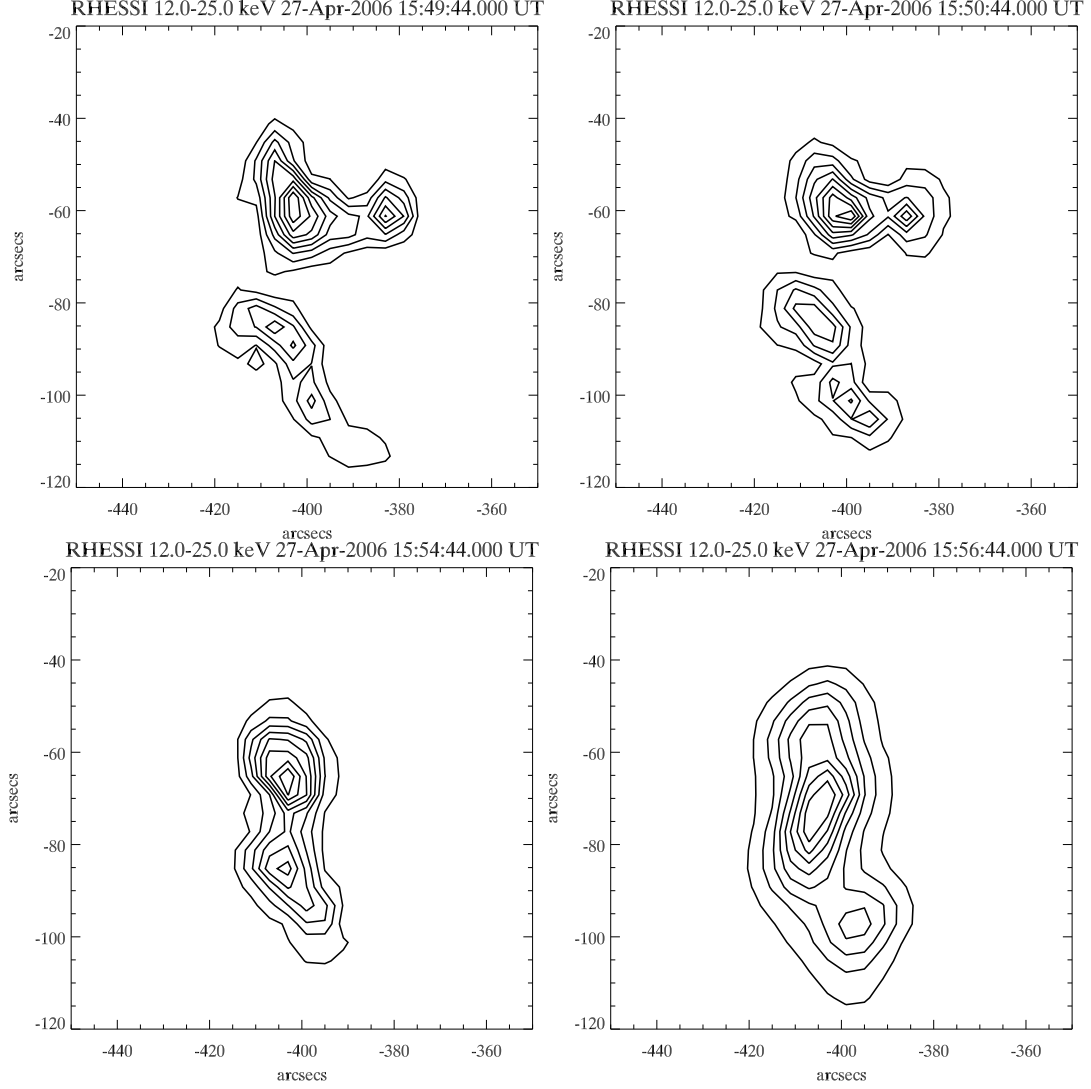


Fig. 9.— RHESSI images in 12-25 keV energy bands reconstructed with the PIXON algorithm (contour levels for each image are 40%, 60%, 80% and 95% of peak flux).

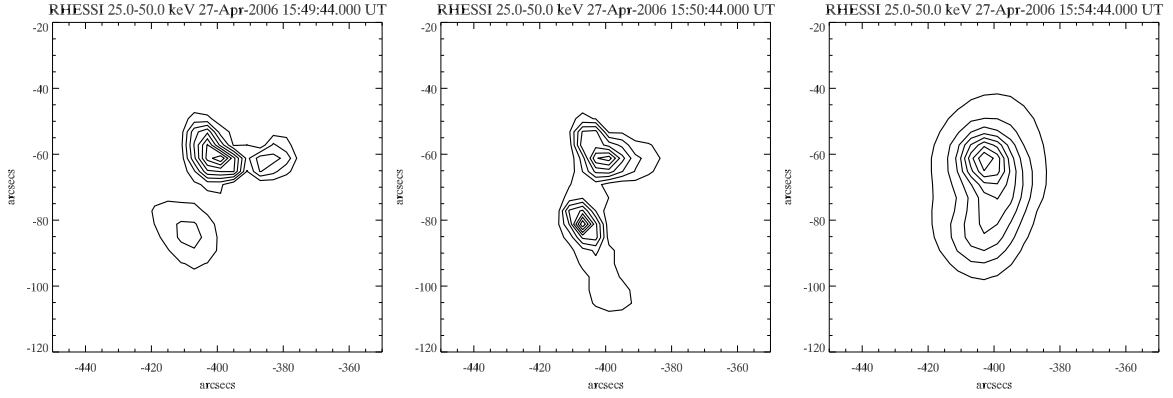


Fig. 10.— RHESSI images in 25-50 keV energy bands reconstructed with the PIXON algorithm (contour levels for each image are 40%, 60%, 80% and 95% of peak flux).

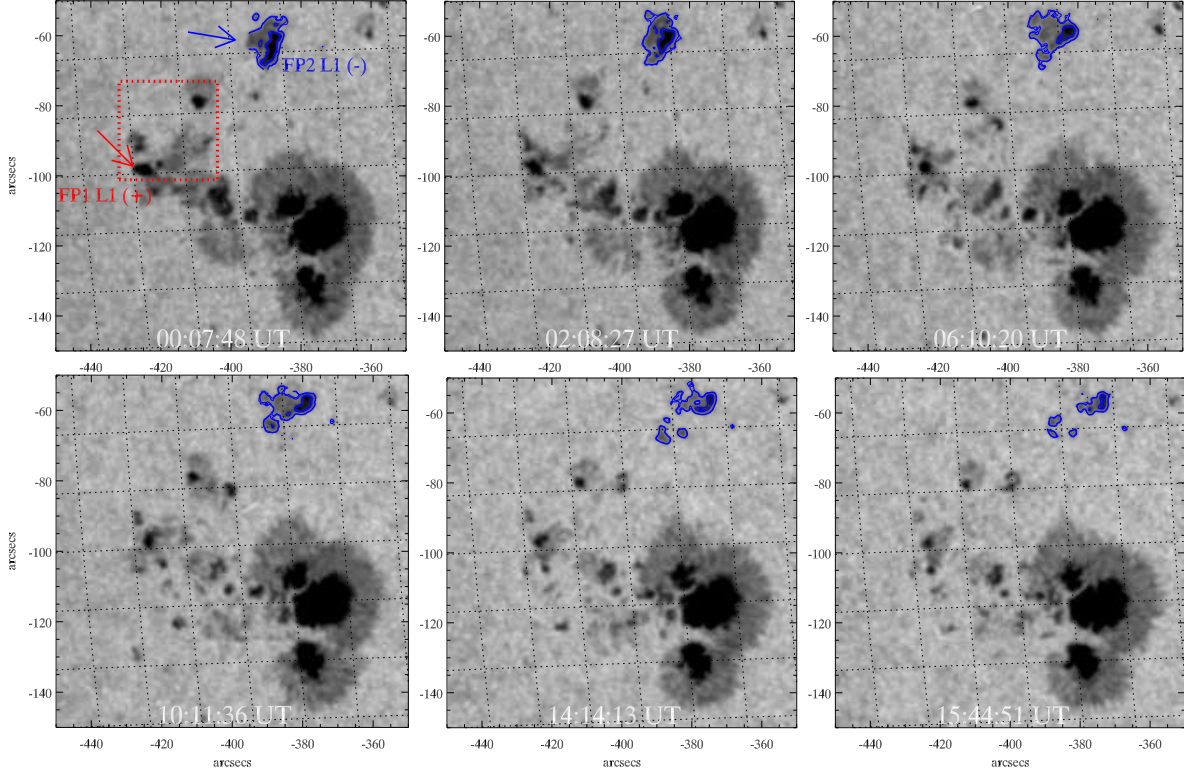


Fig. 11.— TRACE white-light images of the active region showing the linear/shear motion of negative polarity sunspot (indicated by blue contours). FP1 (red) and FP2 (blue) in the top first image show the ‘+ve’ and ‘-ve’ footpoints (indicated by arrows) of the lower loop system respectively.

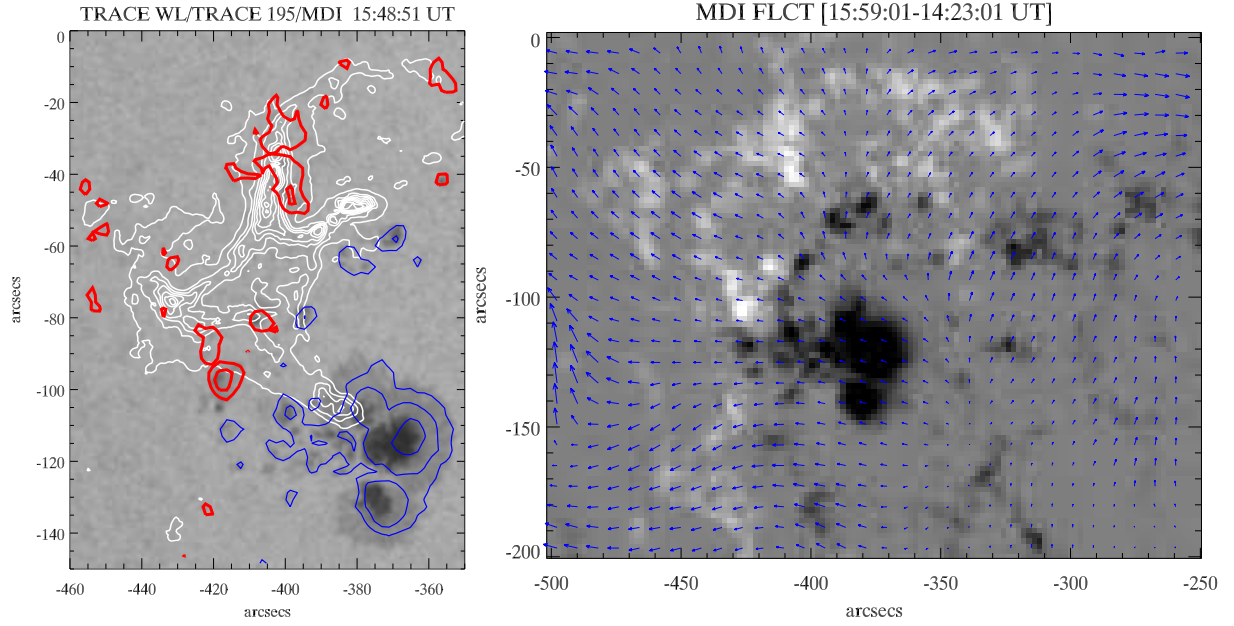


Fig. 12.— Left: TRACE 195 Å (white) and MDI magnetogram contours overlaid on TRACE white-light image. Red contours indicate the positive polarity sunspots whereas blue one show the negative polarity spots. The contour levels are  $\pm 500, \pm 1000, \pm 2000, \pm 3000$  G. Right: The photospheric velocity map obtained from FLCT (Fourier Local Correlation Tracking) technique using SOHO/MDI magnetograms. The longest arrow corresponds to velocity of  $0.291 \text{ km s}^{-1}$ .

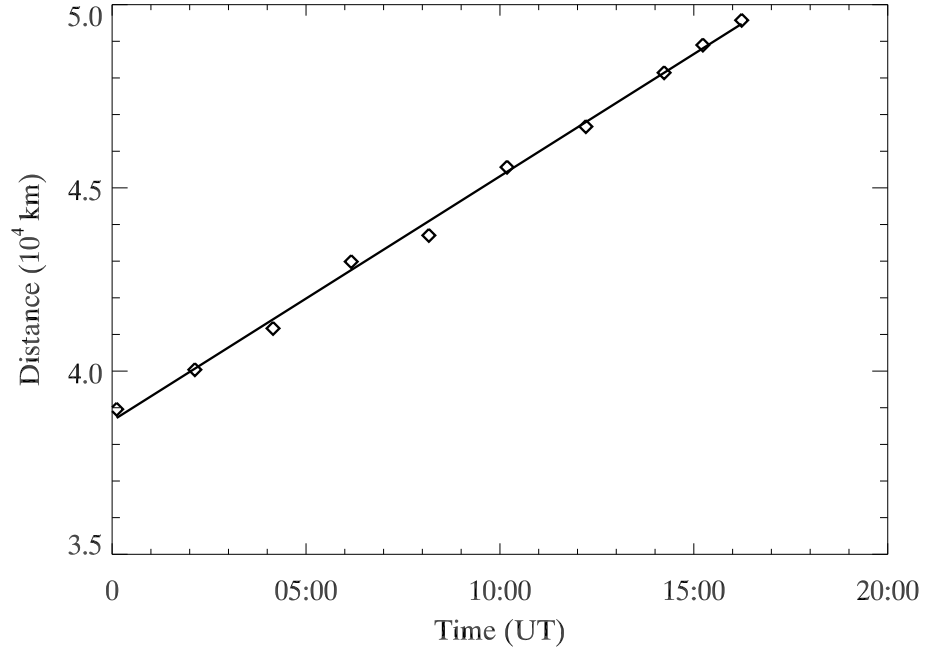


Fig. 13.— The linear motion of negative polarity sunspot on 27 April, 2006. One footpoint of the loop-system was anchored in this sunspot. The estimated speed of the sunspot from the linear fit is  $\sim 0.2 \text{ km s}^{-1}$  ( $662 \text{ km h}^{-1}$ ). This motion probably caused the destabilization and interaction in the loop systems.



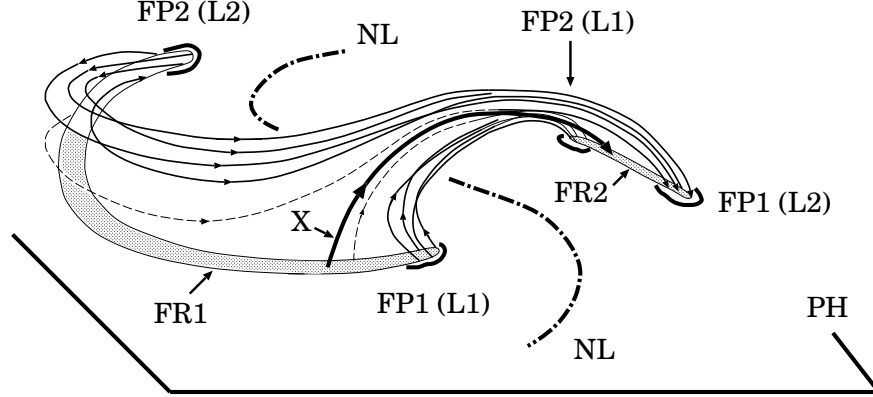


Fig. 14.— Magnetic field lines that connect the  $H\alpha$  kernels FP1 (L1), FP2 (L1), FP1 (L2), and FP2 (L2) are passing through a region of primary energy release located somewhere near the top of the separator X. The flare ribbons FR1 and FR2 are formed where these field lines cross the photospheric plane PH. NL is the neutral line of photospheric magnetic field. Chromospheric evaporation creates a picture of the crossing soft X-ray loops.

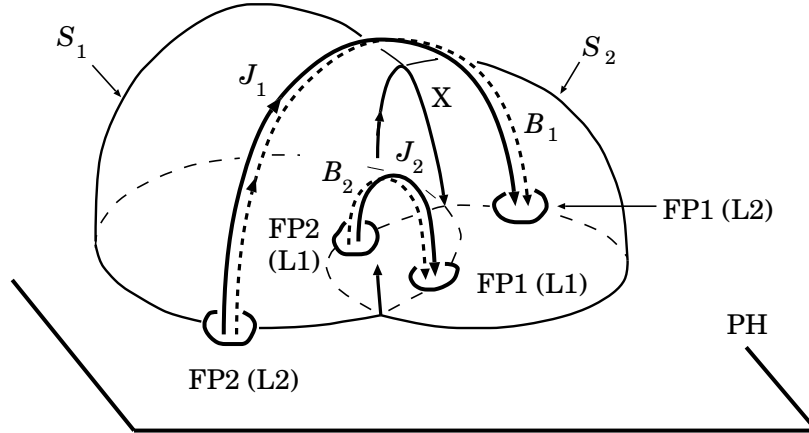


Fig. 15.— A 3D model of the coronal magnetic field with two interacting electric currents  $J_1$  and  $J_2$ . Four magnetic fluxes of different linkage are separated by the separatrices  $S_1$  and  $S_2$  that cross at the separator X above the photospheric plane PH. The two field lines  $B_1$  and  $B_2$  connect the kernel FP2 (L2) with FP1 (L2) and the kernel FP2 (L1) with FP1 (L1). The coronal currents are distributed somehow inside the two magnetic cells and are shown schematically as the total currents  $J_1$  and  $J_2$  along the field lines  $B_1$  and  $B_2$ .

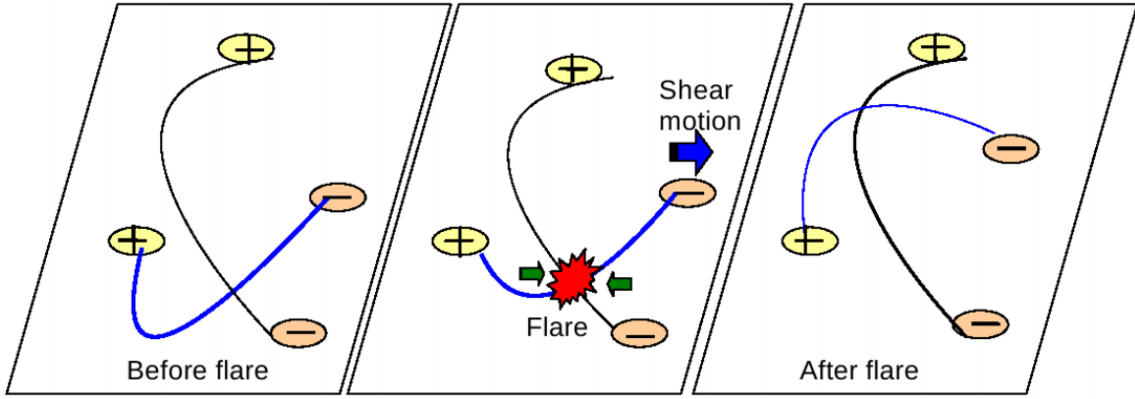


Fig. 16.— Schematic cartoons showing the flare triggering due to interaction of two X-ray loop-system. Black line shows the higher-loop system and dark blue line indicates the smaller underlying loop system. Due to shear motion of the right footpoint of smaller loop system, it becomes unstable and reconnects with the overlying higher loop system, triggering a flare event. After the flare event, the lower loop system becomes simplified as evident in GOES SXI image at 16:31:01 UT (Figure 2).